ENERGY-EFFECTIVENESS OF NONTHERMAL PLASMA REACTORS FOR TOLUENE VAPOR DESTRUCTION

By Chia-Hsin Lin[1] and Hsunling Bai[2]

ABSTRACT: The energy-effectiveness of packed-bed and nonpacked-bed plasma reactors for the destruction of toluene vapors is evaluated on the basis of the power consumption of the reactor system. The operation and design parameters being evaluated include the applied voltage, inlet gas flow rate, and toluene concentration. The optimal operational conditions for the target destruction of toluene vapors, with minimum power consumption, are determined. The results showed that a packed-bed plasma reactor has a higher toluene destruction efficiency and a lower power consumption than a nonpacked-bed plasma reactor. The toluene destruction efficiency is increased as both the inlet gas flow rate and the toluene gas concentration are decreased. For a plasma reactor 2 cm in diameter and packed with 5-mm glass pellets, >90% of toluene destruction can be reached at an applied voltage of 8.7 kV, inlet toluene concentrations <1,000 ppm, and gas flow rates of <680 cm^3/min. The corresponding energy-effectiveness is about 15 g toluene/kW·h.

INTRODUCTION

Nonthermal plasma techniques for removal of various gaseous pollutants have been widely evaluated over recent years. They are known to be highly effective in promoting oxidation, enhancing molecular dissociation, or producing free radicals to increase removal rates of pollutants such as NO_x, SO_x, and volatile organic compounds (VOCs). The nonthermal plasma techniques include the electron beam reactor (Vitale et al. 1996), pulsed corona reactor (Chang and Masuda 1988; Yamamoto et al. 1992), dielectric barrier discharge reactor (Higashi et al. 1985; Rosocha et al. 1993; Chang and Chang 1997), and packed-bed plasma reactor (Yamamoto et al. 1992; Futamura et al. 1995).

The dielectric barrier discharge reactor employs silent discharges to generate nonthermal plasmas in which energetic electrons excite, dissociate, and ionize gas molecules to form free gas radicals, thereby driving either gas phase or heterogeneous reactions of decomposition and oxidation of air pollutants such as VOCs into end products—including H_2O, CO, and CO_2—that are less hazardous to the environment and human health. The packed-bed plasma reactor is an extended design of the dielectric barrier discharge reactor. It is usually a tubular glass reactor packed with high dielectric pellets. An AC (50–60 Hz) high voltage power is applied across the high dielectric layer (Yamamoto et al. 1992), the reactor is energized, the pellets are polarized, and an intense electric field is formed around each pellet contacting point, resulting in microdischarge. The packed-bed plasma reactor behaves similarly to the dielectric barrier discharge reactor except that the microdischarge occurs at each contact point of the pellets, which distributes uniformly across the gas flow in the packed-bed reactor, but it occurs on the flat dielectric surface in the dielectric barrier discharge reactor (Yamamoto et al. 1996). The study of Futamura and Yamamoto (1997) showed that the packed-bed plasma reactor operates with a relatively small-volume fraction of plasma but with a large surface area of materials that can be catalytically activated by free radicals from the plasma.

The study of Yamamoto et al. (1992) was the first attempt to develop baseline engineering data on the application of a packed-bed nonthermal plasma reactor to the destruction of various VOCs. The influencing factors such as the inlet gas concentration, corona power, packing materials and packing size, and gas flow rate on the effects of the VOCs' destruction efficiency were studied. Other studies of the packed-bed plasma reactor were mainly focused on the destruction of efficiencies of various pollutants (Yamamoto and Jang 1996) and by-product identification (Futamura and Yamamoto 1997). Limited information is available on the energy-effectiveness analysis of the packed-bed and nonpacked-bed reactors. The energy consumption is one of the major factors for the field application of a plasma reactor.

PREEVALUATION OF OPERATION AND DESIGN PARAMETERS

The operation and design parameters under consideration included the reaction temperature, oxygen concentration and relative humidity of the system, packing material and packing size, applied voltage across the reactor, diameter of the reactor, inlet gas concentration, and gas flow rate (or gas retention time in the reactor). All of these parameters have more or less been evaluated in the literature. However, a preevaluation of each design and operation parameter to determine its relative importance is necessary to reduce the complication of the energy-effectiveness analysis.

In this study the experiments were conducted at a room temperature that is typical for emissions from the semiconductor industry. Chang and Chang (1997) indicated that increasing the gas temperature could improve the toluene destruction in a nonthermal plasma system. But if the reactor temperature has to be increased, it consumes more energy and may result in a lower energy-effectiveness value. In addition, it increases the complication of a reactor design. Thus the temperature effect was not included in the evaluation.

The studies of Atkinson and Lloyd (1984) and Emdee et al. (1992) indicated that the reaction of toluene with an OH radical is the most important pathway leading to its destruction. The OH radical is mainly formed because of the dissociation and ionization of O_2, H_2O, and toluene by the collision with energetic electrons. Therefore increases in the oxygen and moisture contents may lead to increases in the toluene removals. The study of Chang and Chang (1997) has shown that a plasma reactor operated at a higher oxygen content apparently has a better toluene destruction efficiency than at a lower oxygen content. Thus, in this study, the oxygen content was controlled at around 20%, which is a typical value for emissions from the semiconductor industry. Besides, a control of the rel-

---

[1] PhD Student, Inst. of Envir. Engrg., Nat. Chiao-Tung Univ., 75 Po-Ai St., Hsin-Chu 300, Taiwan.

[2] Prof., Inst. of Envir. Engrg., Nat. Chiao-Tung Univ., 75 Po-Ai St., Hsin-Chu 300, Taiwan. E-mail: hlbai@green.ev.nctu.edu.tw

Note. Associate Editor: Mark Rood. Discussion open until December 1, 2001. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on December 5, 1999; revised February 9, 2001. This paper is part of the ***Journal of Environmental Engineering***, Vol. 127, No. 7, July, 2001. ©ASCE, ISSN 0733-9372/01/0007-0648–0654/$8.00 + $.50 per page. Paper No. 22141.

J. Environ. Eng. 2001.127:648-654.

ative humidity can be done simply by an installation of the humidifying system and the experimental tests in this study were conducted at the high relative humidity of 95% to increase the toluene removal.

Packing material and pellet size are two other important parameters that require extensive studies. Yamamoto et al. (1992) conducted experiments on the effect of three different pellet sizes (0.1, 0.3, and 0.5 cm) of $BaTiO_3$ on the toluene removal, and the results did not show a clear trend as the pellet size varied. On the other hand, a further study of Yamamoto et al. (1996) was conducted to evaluate the effect of different pellet materials on the CCl_4 destruction efficiency. The results indicated that the use of Co, Cu, Cr, and V catalysts coated on the $BaTiO_3$-based pellets did not show a better CCl_4 destruction but the Ni catalyst that coated on the $BaTiO_3$-based pellets did increase the CCl_4 destruction and reduce the CO formation as well. Mizuno et al. (1996) also found that the discharge intensity of packing materials with a high dielectric constant is apparently larger than that of packing with low dielectric constant materials under the same applied voltage and frequency.

In conclusion, there are two mechanisms leading to the enhancement of the VOCs' removal using a packed-bed plasma reactor. One is due to the catalytic effect at the surface of the packing materials (Yamamoto et al. 1996; Futamura and Yamamoto 1997). The other is due to enhancement in the microdischarge intensity by means of the use of packing materials with a high dielectric constant (Mizuno et al. 1993). In addition, packing with the same material but different shapes may also influence capacitance and lead to a change in microdischarge intensity and removal efficiency as well. Because of the availability of packing material with a high dielectric constant (such as $BaTiO_3$), this study employs a spherical glass pellet whose dielectric constant is only 5. And a pretest on an Al_2O_3 pellet whose dielectric constant is 6 was also conducted and compared to the results of using glass pellets. The results showed that, at low applied voltages, the Al_2O_3 pellets produced a higher toluene destruction efficiency but, at high applied voltages, the glass pellets performed better. Because the purchase price of glass pellets is cheap, the following study employed glass pellets of 0.5-cm diameter.

The variation in the diameter of a nonthermal plasma reactor used in recent studies was not much; the reactor diameter ranged from around 1.5 cm (Yamamoto et al. 1996) to 3.6 cm (Chang and Chang 1997). In this study, pretests of the effect of reactor diameter ranging from 2.0 to 3.0 cm showed that the toluene removal efficiency increases as the reactor diameter decreases. This may be because the electric field strength is higher for a small reactor under the same applied voltage. In the following study, a reactor with a diameter of 2.0 cm was used to increase the toluene destruction efficiency.

The remaining key parameters that require further evaluation are the gas flow rate, toluene inlet concentration, and applied voltage. The following experiments were done to evaluate their effects on the toluene destruction efficiency and the energy effectiveness of the reactor.

MATERIALS AND METHODS

The experimental setup is shown schematically in Fig. 1. The inlet toluene vapors were obtained by passing purified N_2 gas through two impingers in series, which were kept in a water bath at a constant temperature. The N_2 carrier gas was saturated with toluene vapors after passing through the first impinger containing liquid toluene. The second impinger was empty so as to knock out any toluene liquid droplets in the carrier gas. Another two streams of clean, compressed air were served as the diluting and humidifying gases. The clean air

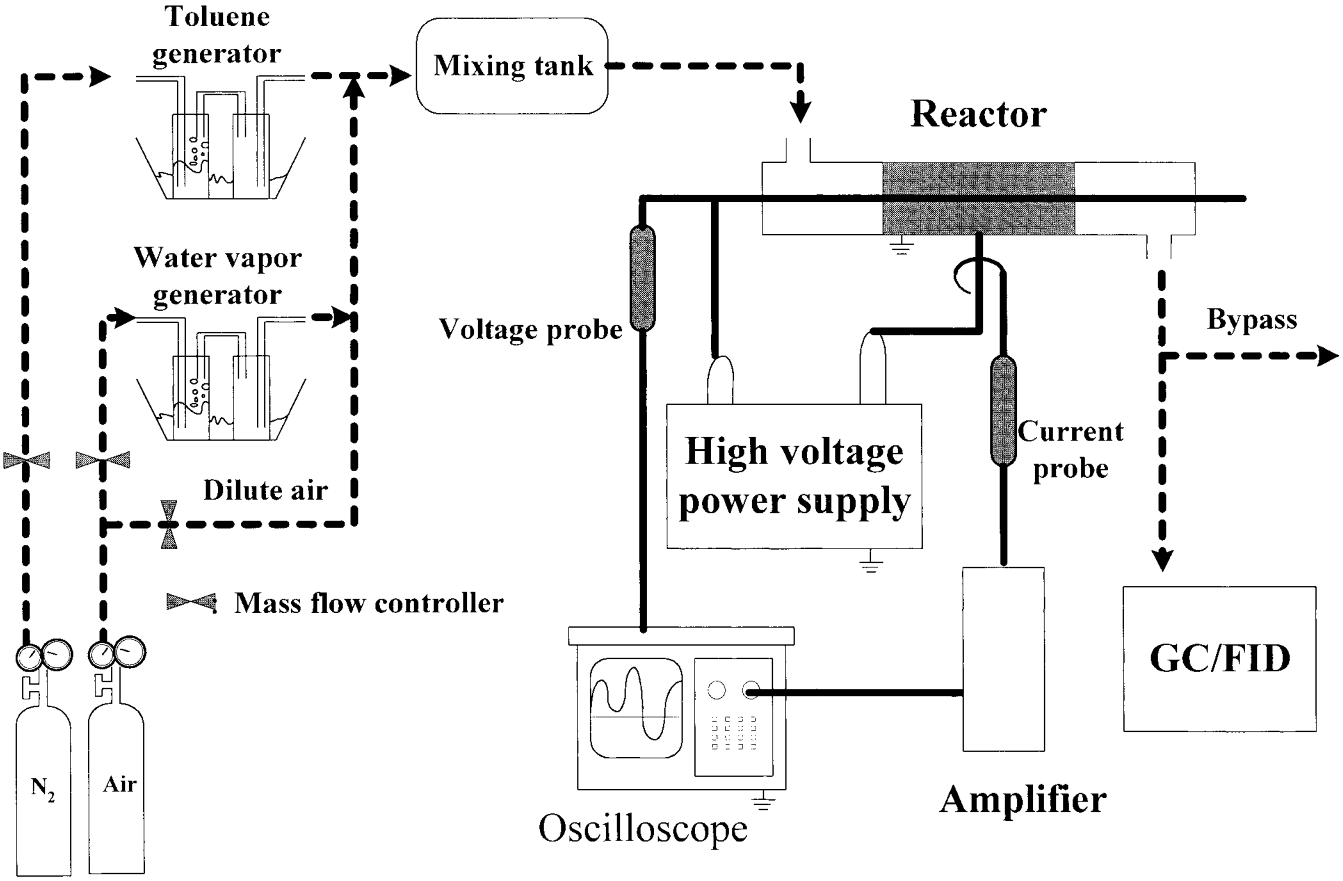

FIG. 1. Schematic of Experimental Setup

J. Environ. Eng. 2001.127:648-654.

was provided by passing the airstream through a silica gel air dryer and a Gelman-TDC filtration system. The arrangement of the humidifying system was similar to that of the toluene vapor producing system except that the first impinger in the humidifying system contained deionized water. The flow rates of all gaseous streams were controlled by mass flow controllers (MKS, Andover, Mass.). The toluene inlet and outlet concentrations were analyzed by a gas chromatographic system coupled with a flame ionization detector (GC-FID) (Shimadzu-GC14B, Kyoto, Japan) and a fused silica capillary column (SGE, BX5: 50-m length, 0.053-cm inner diameter). The toluene vapor concentrations before the inlet of the reactor were controlled to be within ±5% variation during the testing period. And replicate data of the toluene outlet concentration were within 5% deviation. All experiments were done at room temperatures of around 23 ± 2°C. The relative humidity was controlled at around 95%, as measured by a humidity sensor (Rotronic, Model CH 8040, Swiss).

The plasma reactor was a tubular glass reactor with 2.0-cm inner diameter and 2.4-cm outer diameter. When it was packed, spherical glass pellets of 0.5-cm diameter were held in the reactor by two glass meshes. The packing length was 15 cm. The inner electrode was made of stainless steel, with a diameter of 0.2 cm. The outer electrode was also made of stainless steel, with a form of wire mesh that wrapped around the outside of the glass tube reactor. The length of the outer electrode was the same as the packing length.

The applied voltage to the reactor was adjusted by varying the primary voltage of the transformer, and the reactor was energized with 60-Hz AC at up to 11.7-kV root-mean-square. The power of the whole system and the reactor itself are measured with the power meter and oscilloscope, respectively. The whole system power consumption is measured with a read-out multimeter (TES, Model 2700, Taipei, Taiwan) connected to the primary voltage end. A digital real-time oscilloscope (Tektonix, Model TDS 340A, Beaverton, Oreg.) is used to measure high voltage-end power consumption. The accuracy of the oscilloscope is ±2%. A 40-kV peak-to-peak voltage probe (Tektronix, Model P6015A, Beaverton, Oreg.) and a current probe amplifier (Tektronix, Model A6302 and AM 503B, Beaverton, Oreg.) were connected to the secondary voltage end and the oscilloscope. The signals of voltage and AC current were transmitted to the oscilloscope synchronously after attenuation, and the instantaneous power consumption was determined based on the product of the voltage and AC current. The instantaneous power consumption was recorded in a frequency of 1 s^{-1}. And the average reactor power consumption was calculated based on a period of 5-min measurement data.

RESULTS AND DISCUSSION

Analysis of System and Reactor Power

Electric power consumption is the major operation cost of a plasma reactor. To understand the energy-effectiveness of a plasma reactor, it is necessary to evaluate the fraction of power that is consumed to the whole system and to the reactor itself. Fig. 2(a) shows the relationship between the applied voltage and the toluene destruction efficiency. Fig. 2(b) shows the relationship between power consumption and the toluene destruction efficiency. The experiments were done at a toluene inlet concentration of 500 ppm and a gas flow rate of 500 cm^3/min. It is seen from Fig. 2(a) that, as the applied voltage was <8.5 kV, the toluene destruction efficiency increases rapidly as the voltage increases. The corresponding toluene destruction efficiency is around 90% at 8.5 kV. A further increase in the applied voltage increases the toluene destruction efficiency gradually. The power consumptions of the whole system as well as the reactor itself show similar trends to the applied

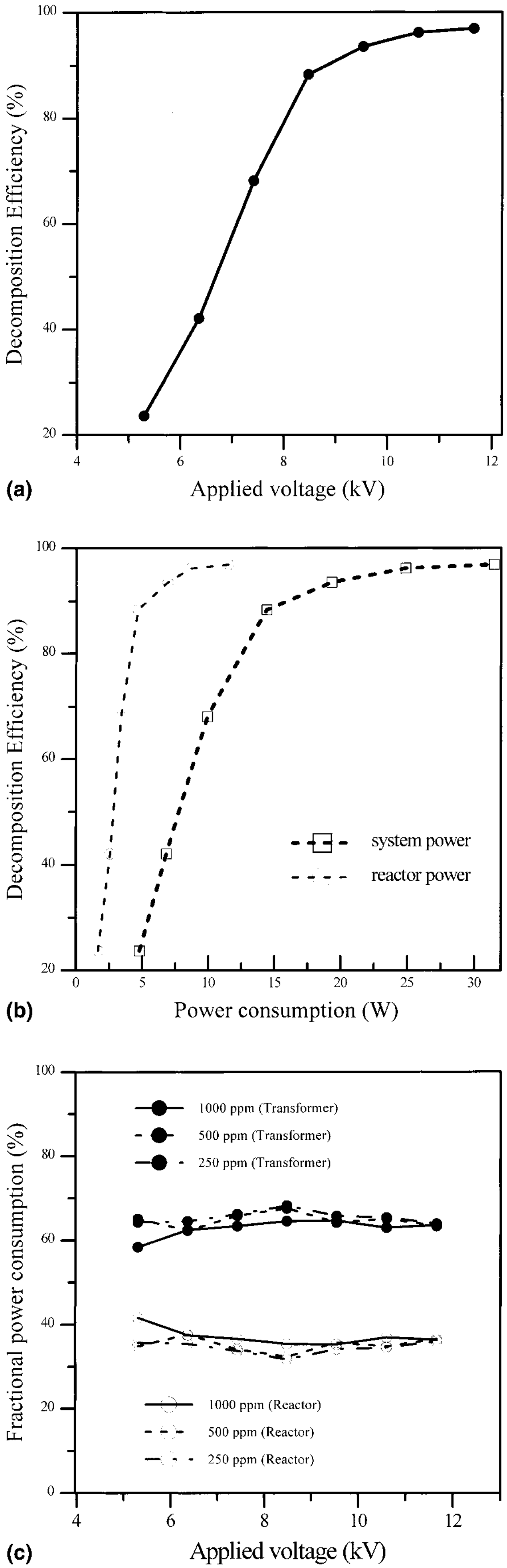

FIG. 2. For Packed-Bed Reactor: (a) Toluene Decomposition Efficiency as Function of Applied Voltage; (b) Toluene Decomposition Efficiency as Function of Power Consumption; (c) Fractional Power Consumptions of Transformer and Reactor at Different Toluene Inlet Concentrations

voltage, as shown in Fig. 2(b). If the toluene destruction efficiency is to be increased from 90 to 98%, the power consumption would have to be doubled.

One can also see from Fig. 2(b) that the reactor consumed less than half of the whole system power. This is further demonstrated in Fig. 2(c), which shows the fractional power consumptions of the transformer and the reactor under different toluene inlet gas concentrations as a function of applied voltage. It indicates that the power consumption fractions of both the transformer and the reactor for a packed-bed reactor are not changed as the applied voltage is varied. The transformer loss contributed around 60% of the system power consumption. The power consumption fractions under different inlet gas flow rates are similar to those under different inlet toluene concentrations and hence are not shown. Conclusively, the power distributions between the system and the reactor are constant under different operational conditions using the same power device. As a result, in addition to an optimal design on the plasma reactor to reduce the system cost, an improvement in the transformer design is also necessary, which may significantly reduce the power consumption of the plasma reactor system. However, this is beyond the ability of an environmental engineer.

Packed- and Nonpacked-Bed Plasma Reactors

The performance of packed-bed and nonpacked-bed plasma reactors was compared and the results are shown in Figs. 3(a and b) in terms of the toluene destruction efficiency and the power consumption, respectively. Note that both packed-bed and nonpacked-bed reactors were operated at an inlet gas flow rate of 1 liter per minute for the same reactor geometry; thus, the residence time is shorter for a packed-bed reactor. The residence times for packed-bed and nonpacked-bed reactors are 2.7 and 4.7 s, respectively. One can see from Fig. 3(a) that the packed-bed plasma reactor (which was packed with 5-mm glass pellets) has a higher toluene destruction efficiency than that of the nonpacked-bed reactor. This is especially true for the high voltage cases. For example, at a voltage of 11.6 kV, the toluene destruction efficiency reaches 91% for a packed-bed reactor but it is only 66% for a nonpacked-bed reactor, as observed in Fig. 3(a). In addition, as observed in Fig. 3(b), the power consumption of a packed-bed reactor is smaller than that of a nonpacked-bed reactor under the same operational condition. As a result, the glass pellets packed in the reactor not only increase the toluene destruction but also reduce the power consumption.

The energy-effectiveness (g toluene removed/kW · h) is used for comparing the performance of a packed-bed reactor and nonpacked-bed reactor based on the reactor power consumption. The energy-effectiveness analysis shown in Fig. 3(c) indicates that an optimal value appeared in both packed- and nonpacked-bed reactors. It also shows that the packed-bed reactor performs better than the nonpacked-bed reactor. For example, when both systems were operated at their best energy-effectiveness value, the energy-effectiveness for a packed-bed reactor is 11.5 g toluene removed/kW · h when operated at 7.2 kV. And it is only 8 g toluene removed/kW · h for a nonpacked-bed reactor operated at 6.4 kV. But note that the cost of packing materials was not included in the comparison. If the cost of glass pellets was included, the cost-effectiveness of a packed-bed plasma reactor should also be better than the nonpacked-bed reactor because the purchase price for glass pellets is very cheap. Therefore, although the dielectric constant of glass pellets is only 5, the packed-bed reactor shows a much better cost-effectiveness than the nonpacked-bed reactor. The effectiveness of a packed-bed reactor is due to the small air gap between the pellet layer reducing the total capacitance, especially when larger dielectric constant pellets were packed,

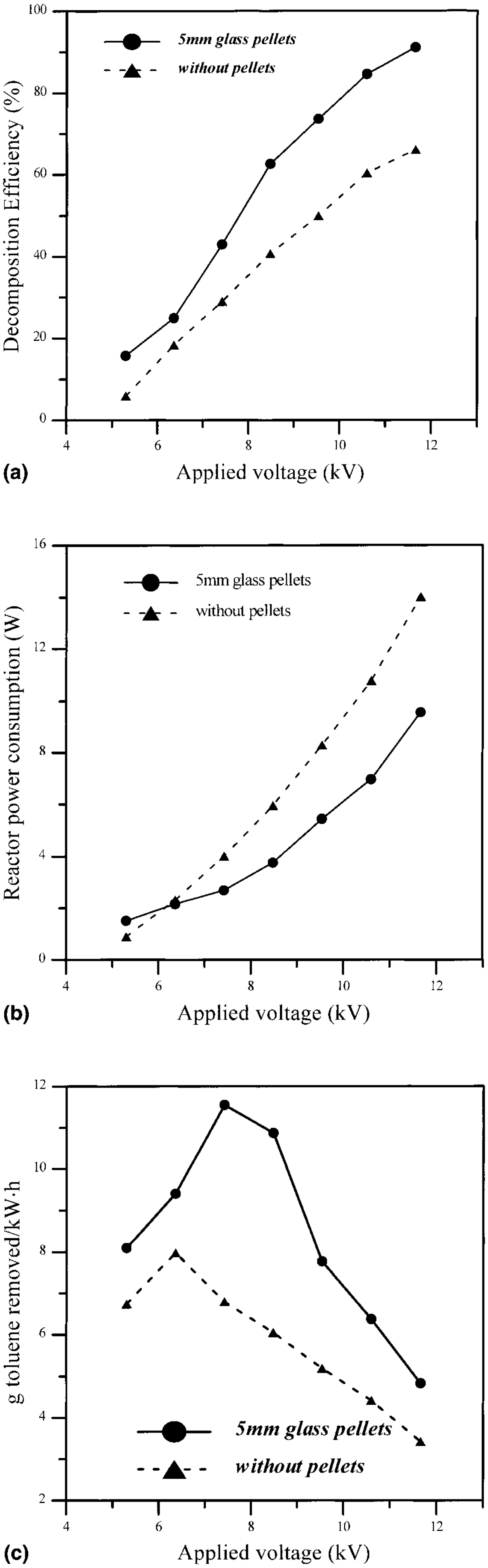

FIG. 3. Packed-Bed versus Nonpacked-Bed Plasma Reactors: (a) Toluene Decomposition Efficiency; (b) Reactor Power Consumption; (c) Cost-Effectiveness Values

and intensive partial discharge initiating at a lower level (Mizuno et al. 1996). However, note that, although the packed-bed plasma reactor has an economical advantage over a nonpacked-bed reactor in the removal of toluene vapors, it may produce by-product gas such as N_2O while decomposing VOCs under certain operational conditions (Futamura et al. 1998). In addition, the pressure drop across the packed bed is higher than that of the nonpacked bed, which may be a concern to some industrial plants.

Although high dielectric constant materials such as $BaTiO_3$ are not available, a comparison of the effect of packing materials on the toluene removal can still be made using data obtained in the literature. Fig. 4 shows the comparison results of toluene destruction efficiency as a function of applied voltage for plasma reactors packed with 5-mm glass beads (this study) and 5-mm $BaTiO_3$ pellets (Yamamoto et al. 1992). The dielectric constants for glass and $BaTiO_2$ pellets are 5 and 5,000, respectively. Note that the packed-bed reactors used in this study and Yamamoto et al. (1992) are not exactly the same. The reactor used in the Yamamoto et al. study does not have an inner electrode, whereas the reactor used in this study has an inner electrode. Although the geometry of the packed-bed reactor used in this study was not quite the same as that of Yamamoto et al. (1992), the fundamentals of both reactors to excite energetic electrons are the same. The operational conditions for both reactors were similar at an inlet toluene concentration of around 250 ppm. But the gas flow rate was 0.5 lpm for the glass reactor and 0.2 lpm for the $BaTiO_3$ reactor, respectively. Because the reactor size of Yamamoto et al. (1992) was not described in their study, it is not certain whether the residence times of these two studies were the same.

It is seen in Fig. 4 that the performance of the $BaTiO_3$ has a higher toluene destruction efficiency than that of a glass reactor when the applied voltage is low. However, if the target efficiency is to reach around 90% of the toluene removal rate, the required applied voltages do not show large differences for both reactors. This may be because the molecule structure of toluene vapors is simple, the pulse current produced by a glass-pellets reactor is enough to break the toluene molecule, and a lot of energy is wasted from the higher intensity of the pulse current generated by a $BaTiO_3$-pellets reactor. As a result of considering the wide availability and low cost of glass pellets, the glass-pellets-packed plasma reactor may be more economical than the $BaTiO_3$-pellets-packed plasma reactor for toluene vapor removals. However, a comprehensive study of the cost-effectiveness of both pellets that covers more VOCs is necessary to confirm this.

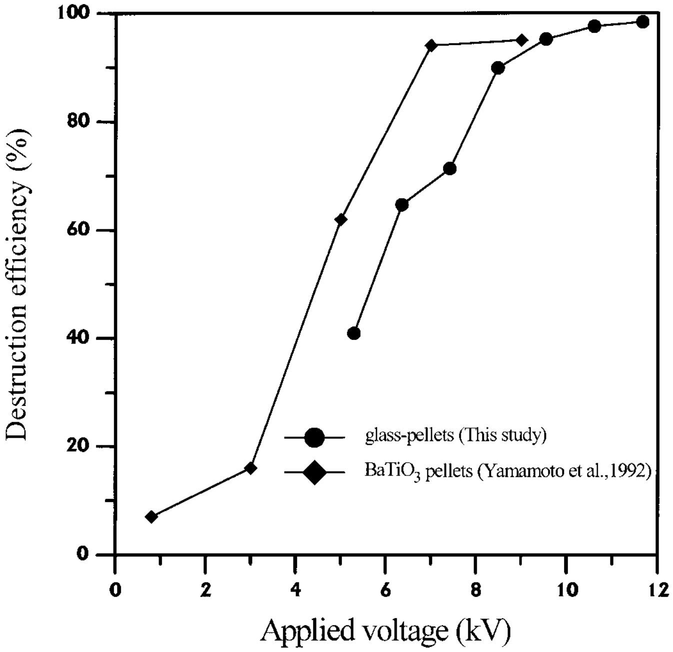

FIG. 4. Comparison of Toluene Decomposition Efficiencies for Packed-Bed Reactors Using Glass Pellets (This Study) and $BaTiO_3$ Pellets (Yamamoto et al. 1992)

Optimal Operation Concentration and Gas Flow Rate

A series of experiments under different inlet gas flow rates and toluene concentrations were done to evaluate the optimal operational condition of the reactor packed with glass pellets. The operation range was set at toluene inlet concentrations of 250–1,000 ppm, total gas flow rates of 500–2,000 cm^3/min, and applied voltage of 0–11.7 kV. To determine the optimal operational condition, both the target toluene destruction efficiency (for example, at least 90% toluene destruction efficiency) and the maximum energy-effectiveness have to be satisfied, but sometimes they are conflicting. As a result, it is the primary objective to meet the minimum toluene destruction efficiency and then determine the optimal operational condition where the maximum energy-effectiveness can be achieved.

Fig. 5 shows contour lines of the energy-effectiveness value (in terms of the reactor power consumption) as well as the toluene removal rate as functions of the inlet gas flow rate and toluene concentration. The data shown in the energy-effectiveness contour lines are in grams of toluene per kilowatthour. Note that, under the operational condition of a high gas flow rate or a high inlet toluene concentration, it becomes less possible to reach >90% of toluene destruction efficiency. For example, when concentration is as high as 1,000 ppm, the inlet gas flow rate should be decreased to less than around 680 cm^3/min to reach 90% toluene destruction. Similarly, if the inlet gas flow rate is at 750 cm^3/min, then the inlet toluene concentration has to be less than around 850 ppm to reach >90% toluene destruction.

On the other hand, if the objective is to achieve high energy-effectiveness of the plasma reactor, one can see from Fig. 5 that the best operational condition is always toward the one that operates at a high gas flow rate and high toluene inlet

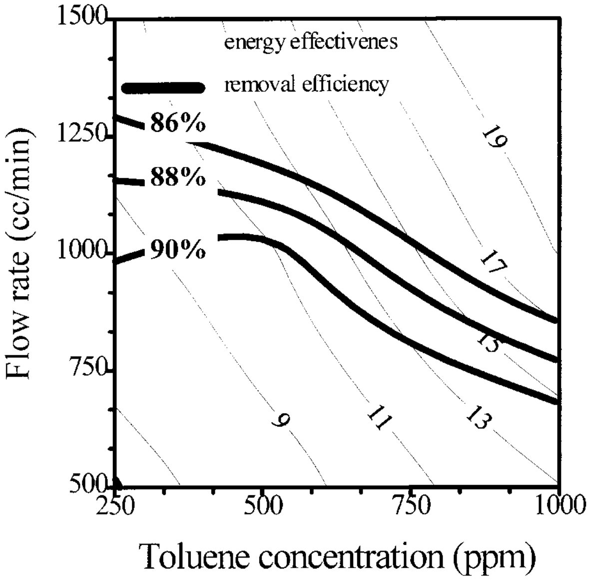

FIG. 5. Contour Plots of Energy-Effectiveness Value As Well As Toluene Destruction Efficiency as Functions of Inlet Gas Flow Rate and Toluene Concentration [Bold Curves Shown in Contour Plots Are Toluene Decomposition Efficiency, and Thin Curves Are Energy-Effectiveness (g toluene/kW · h)]

J. Environ. Eng. 2001.127:648-654.

concentration. This is contrary to the results for the reactor with high toluene destruction efficiency. As a result, the lower the inlet gas flow rate and toluene gas concentration, the higher the toluene destruction efficiency can reach but the energy-effectiveness is reduced. In Taiwan, the emission regulation for the semiconductor industry is based on either at least 90% removal efficiency of <0.6 kg/h of VOC emission. For a plasma reactor of 2-cm diameter and packed with 5-mm glass pellets used in this study, the optimal operational condition to reach >90% toluene destruction and maximum energy-effectiveness is at an inlet toluene concentration of 1,000 ppm and a gas flow rate of 680 cm^3/min. The other operational parameters were kept constant at an applied voltage of 8.7 kV, oxygen contents of around 20%, relative humidity of 95%, and gas temperature of 23°C. Under this operational condition, the system can have >90% of toluene removal with a maximal energy-effectiveness of about 15 g toluene/kW·h.

Practical Applications

Although the optimal gas flow rate and toluene inlet concentration have been determined in this study, the optimal flow rate is too small and the toluene inlet concentration may be too high as compared to the waste gas flow in the field. For the semiconductor industry, the typical emission concentrations of VOCs were at a few hundred parts-per-million levels. They are usually lower than the optimal concentration shown in this study. Therefore a pretreatment of the effluent gas, such as an adsorption-desorption concentrator, can be used to increase the vapor concentration and reduce the gas flow rate. Through the commercialized concentrators available, the VOC concentrations can be approximately 10 times larger than the original concentration and the gas flow rate to be treated can thus be reduced significantly. As a result, the size requirement of the plasma reactor is also significantly reduced.

However, a scale up of the reactor may still be necessary. This can be done by using a reactor with parallel tubes. An experimental test of a multitube reactor was conducted to increase the treated gas flow rate. Two or three reactor tubes of the same size as previously described in this study were connected in parallel arrangement, as shown schematically in Fig. 6. Fig. 7 shows the variations of toluene destruction efficiency and power consumption with the number of reactor tubes installed. The operational condition for a multitube reactor was the same as that for a single-tube reactor as previously described, except that the gas flow rates were doubled or tripled. The inlet toluene concentration was 1,000 ppm, and the applied voltage was 10.8 kV. The gas flow rate in each single tube was 680 cm^3/min. As observed in Fig. 7, all tubes in either the single-tube reactor or the multitube reactor reach similar toluene destruction efficiencies of around 90%. One can also see that the power consumption is linearly increased as the number of reactor tubes increases; this indicates that the energy-effectiveness value of a parallel tube reactor does not deviate from the single-tube reactor. Therefore, a higher gas flow rate can be treated using a multitube reactor and the power consumption for a multitube reactor can also be predicted.

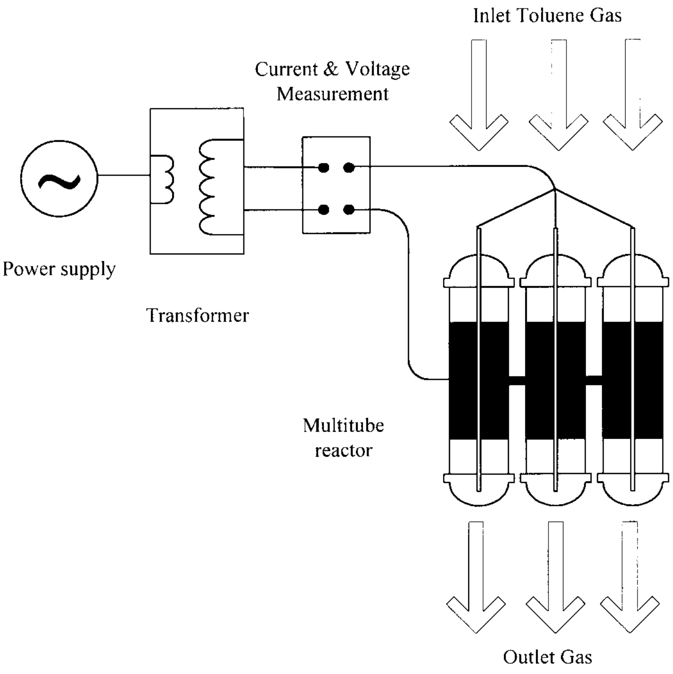

FIG. 6. Schematic of Multitube Reactor System

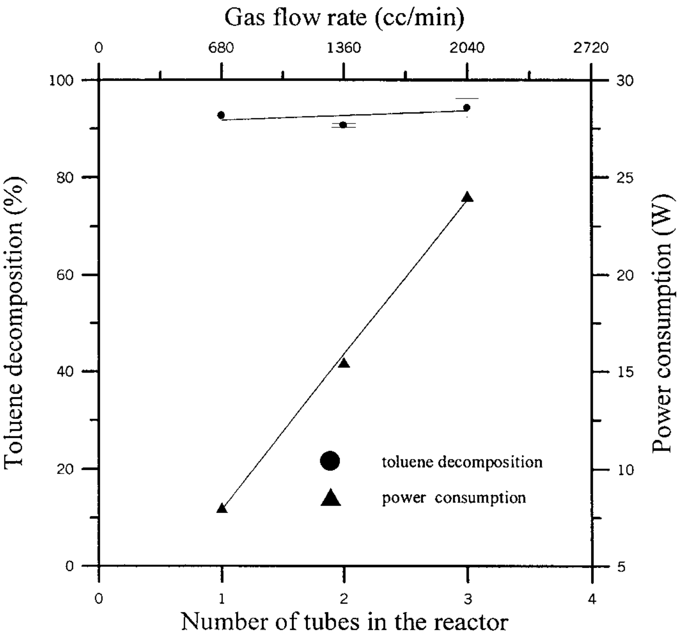

FIG. 7. Toluene Decomposition Efficiency and Reactor Power Consumption as Functions of Number of Tubes Used in Plasma Reactor

CONCLUSIONS

An energy-effectiveness analysis in terms of power consumption is presented in this study to determine the optimal operational conditions for both high toluene destruction efficiency and low power consumption. The results showed that a packed-bed plasma reactor has a higher toluene destruction efficiency and a low power consumption cost than the non-packed-bed plasma reactor, although the reactor is packed with low dielectric constant materials such as glass pellets. The toluene destruction efficiency increases as both the inlet gas flow rate and the toluene gas concentration are decreased.

To achieve a better toluene destruction efficiency and also maintain a high energy-effectiveness, the reactor design may lean toward a low inlet gas flow rate and high inlet toluene concentration. This can be done by a pretreatment of the waste gas with an adsorption-desorption concentrator. A scale up of the reactor can also be done by a parallel-tubes reactor to increase the treated gas flow rate. The results showed that all tubes in either the single-tube reactor or the multitube reactor reach similar toluene destruction efficiencies and the power consumption is linearly increased as the number of reactor tubes increases. This indicates that the energy-effectiveness value of a parallel-tube reactor does not deviate from the single-tube reactor.

Because the optimal operational conditions were determined by considering the toluene destruction efficiency and the

J. Environ. Eng. 2001.127:648-654.

power consumption only, further studies are necessary to determine if the undesired by-products are also minimal under these operational conditions. In addition, the results on the fractions of power consumption by the transformer and the reactor showed that the transformer loss contributed >60% of the system power consumption. Therefore, besides an optimal design of the plasma reactor to reduce the system cost, an improvement in the transformer design is also necessary to reduce the power consumption of the plasma reactor system. However, this is beyond the ability of an environmental engineer.

ACKNOWLEDGMENTS

The writers would like to acknowledge funding provided by the National Science Council (Taipei, Taiwan) of the Republic of China under Project No. NSC 87-2211-E-009-004 for this study.

REFERENCES

Atkinson, R., and Lloyd, A. C. (1984). ‘‘Evaluation of kinetic and mechanistic data for modeling of photochemical smog.’’ *J. Phys. Chem. Reference Data*, 13(2), 315.

Chang, M. B., and Chang, C. C. (1997). ‘‘Destruction and removal of toluene and MEK from gas streams with silent discharge plasmas.’’ *AIChE J*., 43(5), 1325–1330.

Chang, J. S., and Masuda, S. (1988). ‘‘Mechanism of pulse corona induced plasma chemical process for removal NOx and SOx from combustion gases.’’ *Industry Applications Society Annual Meeting*, Vol. 2, 1628–1635.

Emdee, J. L., Brezinsky, K., and Glassman, I. (1992). ‘‘A kinetic model for the oxidation of toluene near 1200 k.’’ *J. Phys. Chem*., 96, 2151–2161.

Futamura, S., and Yamamoto, T. (1997). ‘‘Byproduct identification and mechanism determination in plasma chemical decomposition of trichloroethylene.’’ *Trans. Industry Appl*., 33(2), 447–453.

Futamura, S., Yamamoto, T., and Lawless, P. A. (1995). ‘‘Towards understanding of VOC decomposition mechanisms using nonthermal plasmas.’’ *Trans. Industry Appl*., 31, 1453–1458.

Futamura, S., Zhang, A. H., and Yamamoto, T. (1997). ‘‘The dependence of nonthermal plasma behavior of VOCs on their chemical structures.’’ *J. Electrostatics*, 42, 51–62.

Higashi, M., Sugaya, M., Veki, K., and Fujii, K. (1985). ‘‘Plasma process of exhaust gas from a diesel engine vehicle.’’ *Proc., Int. Conf. Plasma Chem*., 2, 366–371.

Mizuno, A., Yamazaki, Y., Obama, S., Suzuki, E., and Okazaki, K. (1993). ‘‘Effects of voltage waveform on partial discharge in ferroelectric pellet layer for gas cleaning.’’ *Trans. Industry Appl*., 29(2), 262–267.

Rosocha, L. A., et al. (1993). ‘‘Treatment of hazardous organic wastes using sinlent discharge plasma.’’ *Non-thermal plasma techniques for pollution control*, Part B, Berlin; New York, 281–308.

Vitale, S. A., Bromberg, L., Hadidi, K., Falkos, P., and Cohn, D. R. (1996). ‘‘Decomposing VOCs with an electron-beam plasma reactor.’’ *Chemtech*., 26(4), 58–63.

Yamamoto, T., et al. (1992). ‘‘Control of volatile organic compounds by an AC energized ferroelectric pellet reactor and a pulsed corona reactor.’’ *Trans. Industry Appl*., 28(3), 528–533.

Yamamoto, T., et al. (1996). ‘‘Catalysis-assisted plasma technology for carbon tetrachloride destruction.’’ *Trans. Industry Appl*., 32(1), 100–104.

Yamamoto, T., and Jang, B. W.-L. (1996). ‘‘Aerosol generation and decomposition of CFC-113 by the ferroelectric packed-bed plasma reactor.’’ *Trans. Industry Appl*., 32, 1830–1836.

J. Environ. Eng. 2001.127:648-654.